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H4M
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(54) Improvements in or relating to multiplexing and demultiplexing systems

(57) A number of beams of radiation at optical and near-optical wave lengths are multiplexed or demultiplexed by an array 14 of, preferably, variable spatial periodicity, ie a chirped array. The action of the array may be supplemented by a refractive element, eg a lens. As described, a complex light beam, comprising light of different wavelengths and entering the array in the direction 16, is distributed to different foci 18,20,22,24,26 and conversely light beams from the different foci are comeimed into a complex light scan leaving the array in the direction 28. The array consists of radiation reflectors which may be in the form of strips of conducting or dielectric material applied to an optical wave guide. Alternatively the reflectors may be grooves in such a wave guide. In another construction each reflector is an arrangement of applied dots of material. The performance of the array may be altered by modifying the shape and/or size of the individual reflectors systematically along the array.

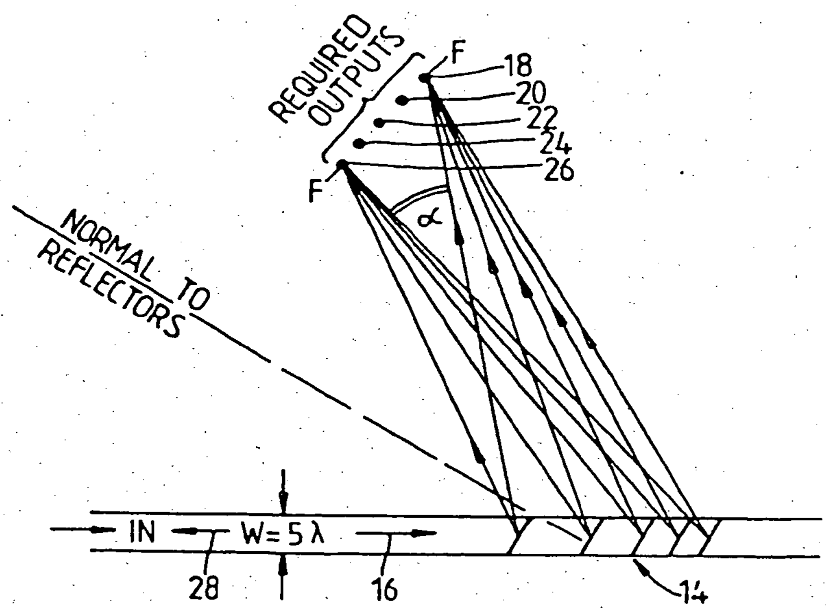

Fig.2.

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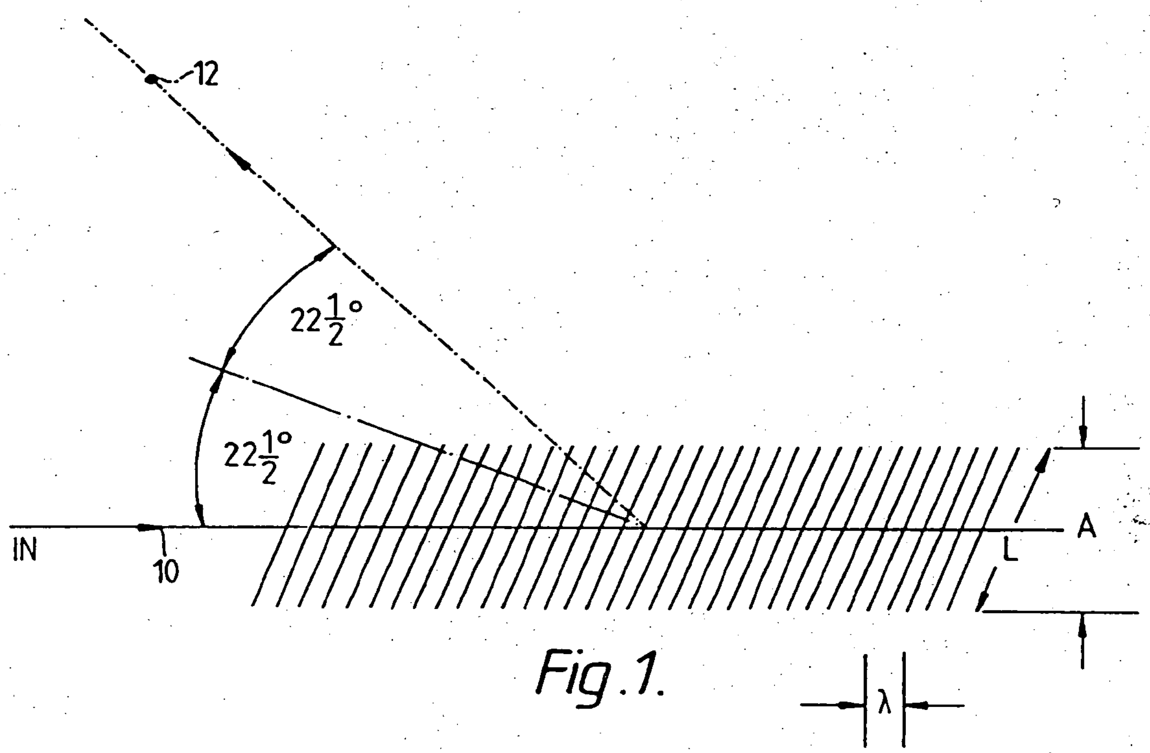


Fig.1.

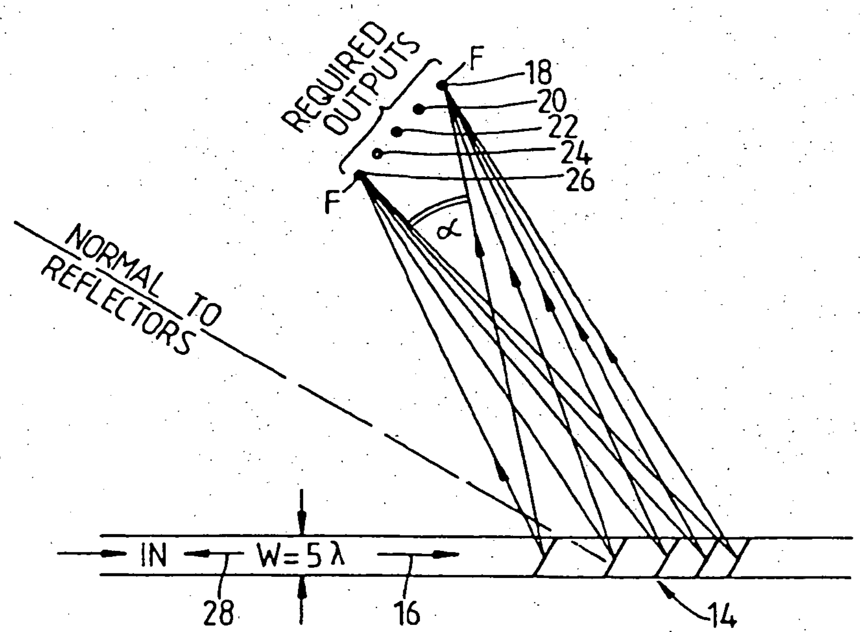


Fig.2.

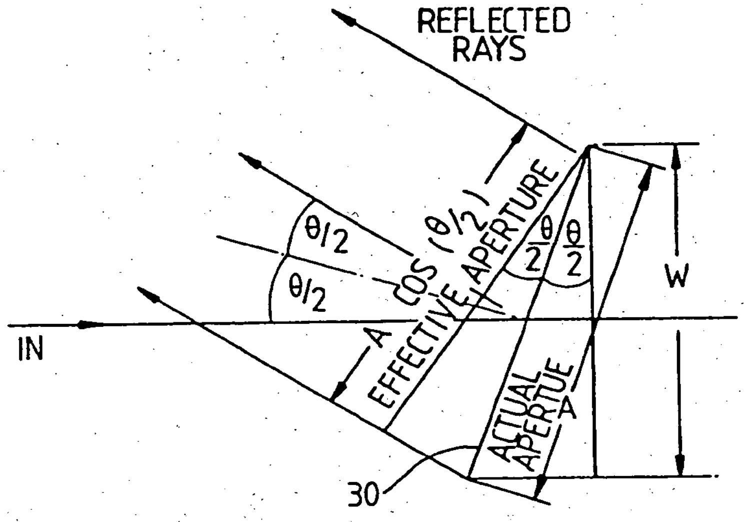


Fig.3.

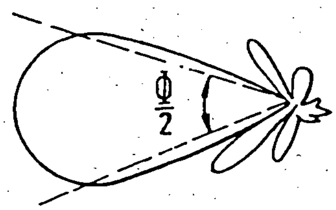
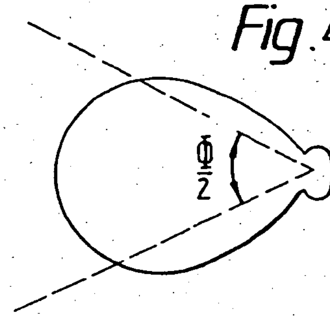


Fig. 4a.

Fig.4b.



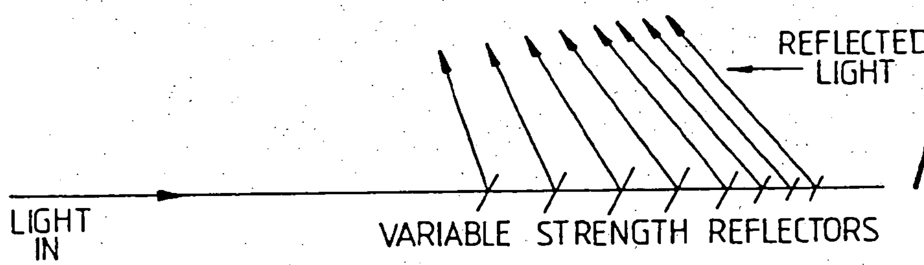
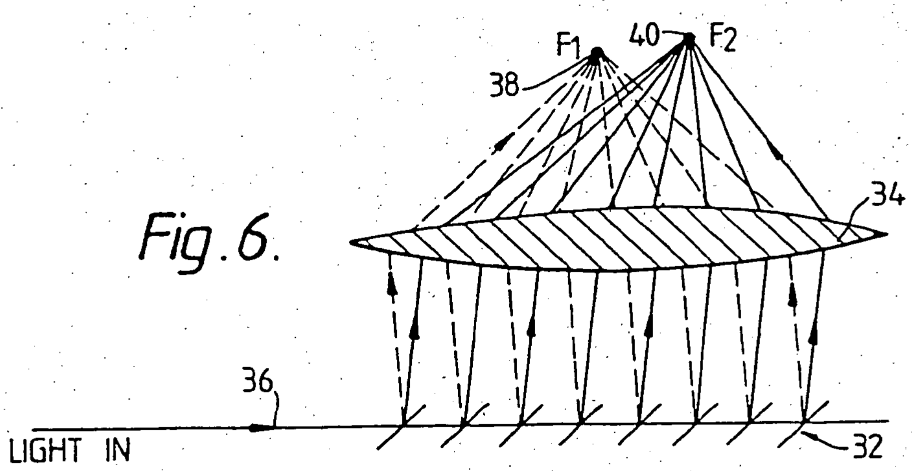


Fig.5.

Fig.6.



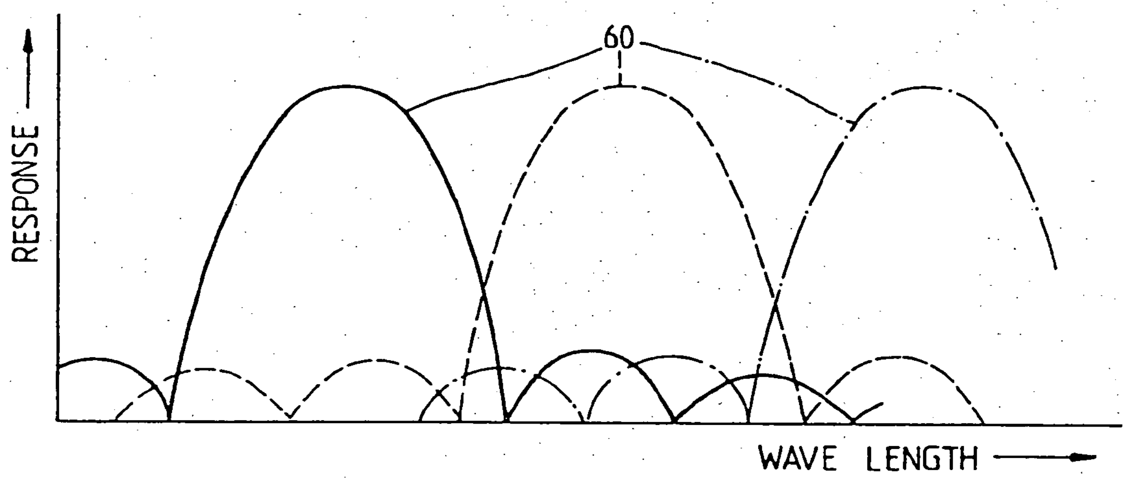


Fig.4c.

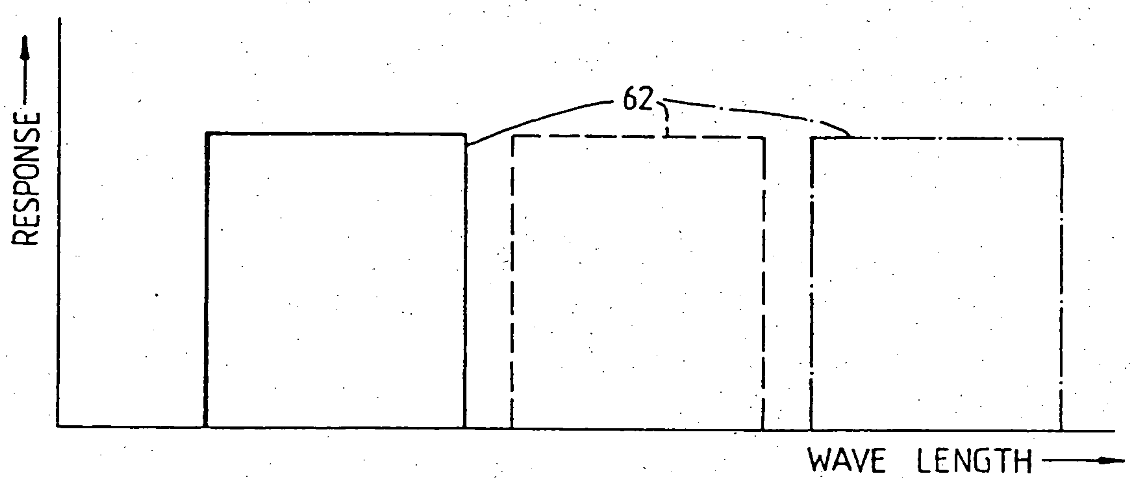


Fig.4d.

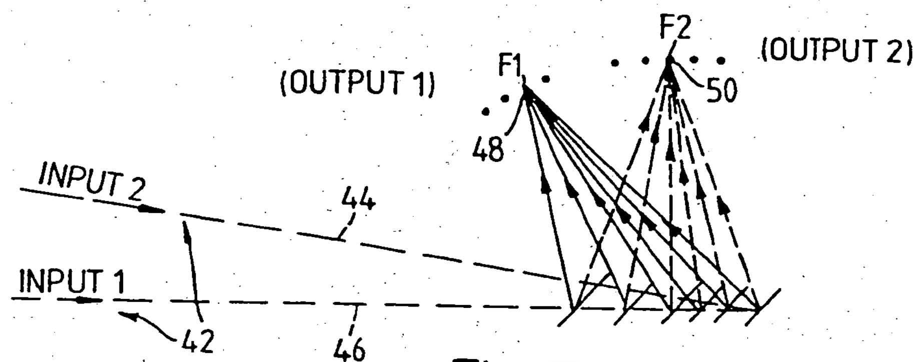
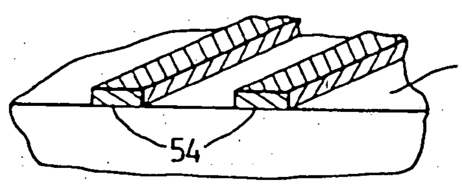


Fig. 7.

Fig. 8a.


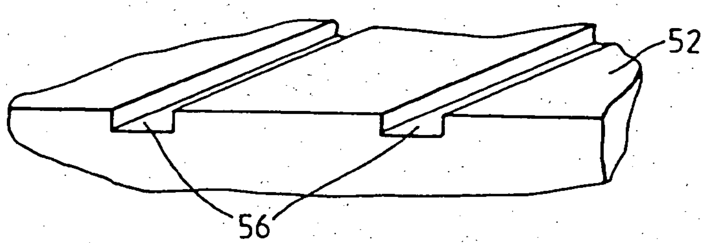


Fig. 8b.

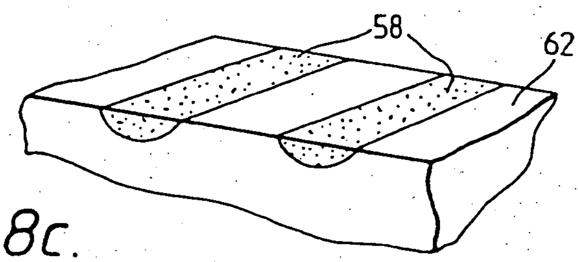


Fig. 8c.

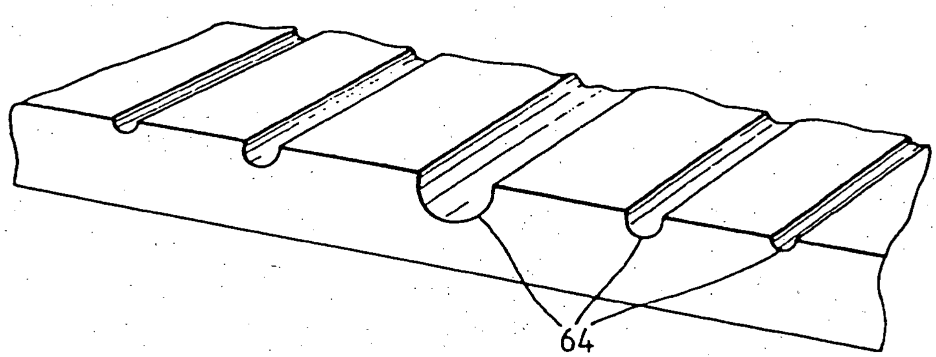


Fig. 9a.

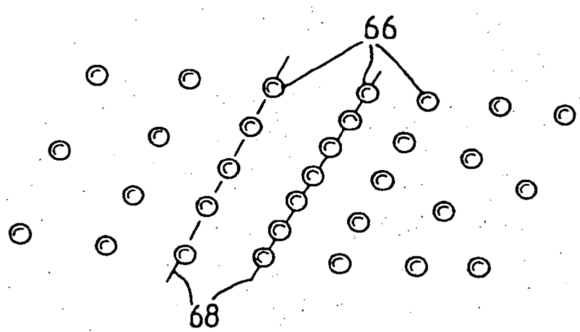


Fig. 9b.

SPECIFICATION

Improvements in or relating to multiplexing and demultiplexing systems

The present invention relates to multiplexing and demultiplexing systems used in the transmission and processing of streams of information. The invention further relates, more particularly, although not exclusively, to systems in which said information streams are carried by beams of electromagnetic radiation, more especially in or near the optical region of the spectrum. Multiplexing and demultiplexing systems have been devised, operating at optical and other frequencies, in which two or more beams of radiation can be combined into one, or one beam separated into two or more. Some relevant prior art references are Yariv, A "Guided-wave optics" Sc. American Jan. 1979 pp 54–62; Malngailis, J et al "16-channel surface-acoustic-wave grating-filter bank for real time spectral analyser" Electronics Letters *10*, 1974 pp 107–109; Barnard, N.E. et al, "The focusing slanted chirped transducer" Proc. IEEE, Ultrasonics Symposium (USA) 1983 pp 205–208.

The present invention provides a system whereby a plurality of radiation beams may be multiplexed or demultiplexed.

According to the invention in a multiplexing and demultiplexing system for the combining and separating of information streams each information stream is carried by one of a plurality of not less than two beams of radiation of predetermined wavelength; combining and separating of said streams being produced by combining and separating the beams carrying said respective information streams at least in part by an array of at least partially reflecting interfaces between media, so shaped and mutually arranged, in relation to the beam or beams to be multiplexed or demultiplexed, as to combine the plurality of beams, emitted from a plurality of discrete foci, to be multiplexed into a combined beam complex; and to separate the component beams from a combined beam complex to be demultiplexed and direct said beams each to be received at one of a plurality of discrete foci.

The combining and separating of the component beams may be produced in part by the said array and in part by a refractive element, for example a lens, associated therewith; the array may then have constant spatial periodicity.

In other embodiments the array has a variable spatial periodicity between the interfaces or reflectors thereof, ie the array is chirped. In the case of a chirped array the reciprocal of the spacing between successive interfaces may vary substantially linearly along the array.

The said interfaces or reflectors may if desir d be curved, and/or may vary in individual size along the array. The interfaces may be arranged as dicrete stripes of material which differs in dielectric constant and/or other physical properties from that of an adjacent continuous bulk of material. Alternatively the interfaces may be arranged as grooves in a surface of a continuous bulk of material. In another embodiment each interface is arranged as a pattern of dots differing in dielectric constant and/or other physical properties from the surroundings; and the reflecting characteristics of such interface may be determined by the size, shape, and/or spacing of said dots.

In a preferred embodiment, the multiplexing and demultiplexing system operates with electromagnetic radiation; preferably in the optical or near-optical regions of the spectrum.

The term "combined beam complex", used in this specification, implies a number of associated component beams of radiation of which some may be, but not necessarily in all instances are, spatially non-coincident for part of their path.

The invention will be further described, by way of example only, with reference to the accompanying drawings, in which

Figure 1 illustrates diagrammatically an array of reflectors having variable spatial periodicity,

Figure 2 illustrates the separation (demultiplexing) of a combined beam complex into a plurality of component beams,

Figure 3 illustrates the effective aperture of an array,

Figures 4A and 4B illustrate angular distribution of radiation from an element of an array,

Figures 4C and 4D illustrate the effect of weighting reflectors in an array,

Figure 5 illustrates one modified form of array,

Figure 6 illustrates a modification of the invention in which an array of reflectors is combined with a refractive element,

Figure 7 illustrates an arrangement whereby two spatially separated combined beam complexes are processed simultaneously by one array.

Figures 8A, B and C illustrate some different ways in which the elements of an array of reflectors can be produced,

Figures 9A and 9B illustrate further ways of weighting reflectors in an array

The array of reflectors illustrated in Fig. 1 is shown at much greater size than would be required for operation at optical wavelengths, for which the invention is particularly useful. As indicated in the drawing, the separation of the reflectors in the array is of the ord r of half the wav length of the radiation employed. The illustration shows only a small number of the reflectors which would be provided in a practical array, which might include from 100 up to about 10,000 reflectors. A characteristic of the array shown in Fig. 1 is that the separation of adjacent reflectors varies from one end of the array to the other, ie it has variable spatial periodicity. Such an array has been re-

ferred to as a "chirped" array. The variation in p riodicity can be arranged according to various plans. One plan of variation, which has been employed in surface acoustic wave (SAW) devices, has the reciprocal of the spacing between the reflectors varying substantially linearly along the array. However, linearity is not essential to the working of the invention, and some departure from it can even produce improved results.

Consider a beam of monochromatic optical radiation (light) directed into the array along the direction indicated by the arrow 10; ie the light is of a given wavelength. A proportion of the light is reflected from each of the reflectors of the array. The effect of the chirped array is that differential phase shifts between neighbouring paths of reflected light all amount to 2π, for the given wavelength, at a point 12. That is to say, at that point all the reflected beams interfere constructively, and 12 is a focal point. At any other point (for the given wavelength) the interference is substantially destructive.

Referring to Fig. 2, the chirped array is indicated generally, and diagrammatically by 14. Consider now a light beam ie a combined beam complex entering the array along the direction of the arrow 16, but in this instance comprising radiation of a number of different wavelengths. The effect of the chirped array is now to concentrate light of the various wavelengths, making up the beam, each at a different focal point; the focal points being indicated by 18, 20, 22, 24, 26. Conversely, a small-cross-section beam of light (eg from an optical fibre) may be directed in at each of the said focal points. The beams will be combined by the array 14 into a combined beam complex leaving the grating in the direction of the arrow 28, to be transmitted where required in a wave guide, which again may be an optical fibre.

Thus if each of the component beams of the combined beam complex is modulated so that it carries a stream of information, the array carries out the function of multiplexing and demultiplexing said information streams, with consequent economy in distant transmission means; ie a plurality of information streams can be carried by one optical fibre wave guide, by frequency (or wavelength) division. If desired, each component beam may be further multiplexed by time division.

The present invention makes use of integrated optical devices, which are planar optical devices. The spatial scale of such device is indicated in Fig. 2, in which the width W of the combined beam complex into (or out of) the array 14 is shown as being 5λ, where λ is about the mean of the wavelength range over which the system is operated. This is, to a first approximation, the width of the individual reflectors in the array. Referring to Fig. 3, for an isotropic substrate, the actual aperture of the reflectors, indicated by A, is determined by th width W of the input beam, just referred to, and the required angle of reflection to the focal points (18 to 26 in Fig. 2). An individual reflector in the array is indicated by 30. If the mean angle through which the input beam is turned by the array, before being brought to foci, is θ, then the reflected beams will have a radiation distribution pattern (Fig. 4A) such that the full angular width between zeroes, $\Phi \simeq 2\lambda/A \cos \theta/2$. The useful width is about half this, ie $\lambda/A \cos (\theta/2)$. If, as exemplified, the input beam has a width of $5\ \lambda$, th useful angular range within which the focal points will lie is approximately λ/W (from Fig. 3, $W=A \cos (\theta/2)$). Hence a is approximately 0.2 radian or 12°. The effect operates to reject unwanted reflections at any other angle from the array.

If the input beam is not a plane wave, having constant amplitude wavefronts across th width W, but has a weighted distribution over the cross section, as in a waveguide with an approximately Gaussian profile, the effect is to produce a wider output angular distribution with reduced unwanted side lobes. This is shown in polar form in Fig. 4B, as compared with Fig. 4A relating to the case of a plane wave.

A weighting effect may be introduced intentionally by modifying the individual reflectors in an array, usually with the object of improving the band shape of a communication channel, and/or reducing interference between channels.

In Fig. 5, for example, the array, as well as being chirped, has reflectors varying in size, from one to the next, along the array, with a corresponding variation in aperture.

The effect of suitable modification of reflectors is illustrated in a much simplified form in Figs 4C and 4D. Fig 4C illustrates the responses of three channels having mid-band wavelengths so spaced that channel response patterns, 60, (of the sin x/x kind) overlap with one another. Such modification of the reflectors of an array, referred to as weighting can produce an effect on the response patterns approximating ideally to that shown in Fig. 4D, in which the overlapping of patterns 62 has been eliminated. To achieve an approximation to such rectangular pass bands it is necessary to implement in the grating a sin x/x weighting function (necessarily truncated). One weighting scheme is shown in Fig. 5, and employs variable reflector lengths. Another scheme keeps all reflectors the same length, but varies their density by omitting some reflectors from the array. In either case the sign reversals required by changes in sign of the sin x/x weighting function can be implemented by means of "jogs" in the reflector positions. For example a "jog" of half a local spatial period will effectively reverse the sign of the reflection coefficient over the wave-

length range of interest.

In a modification of the invention the separation of light beams from a combined complex and bringing them to respective foci (or the reverse process) is effected by a combination of an array with an associated refractive element. This is illustrated diagrammatically in Fig. 6. In this instance the array 32 has uniform spatial periodicity, that is to say the array is not chirped, as in the arrangements described above. In a planar integrated optical device the refractive element will be a lens, which may be of the geodesic, Luneburg or Fresnel kind. Such lenses have been described, for example, in "Acousto-optic Signal Processing' N J Berg and J N Lee, Marcel Dekker Inc New York 1983. An incoming combined beam complex, indicated by the arrow 36, is separated by the array and the lens and is shown being brought to foci 38, 40.

Fig. 7 illustrates a mode of operation, according to the invention, in which two combined beam complexes comprise two component beams 44, 46, which are spatially non-coincident. The beams 44 and 46 may employ the same or different wave lengths and are brought to respective sets of foci 48, 50, the object being to duplicate (or further extend) the basic function of multiplexing and demultiplexing.

An array for use in the invention may be constructed in various ways. Fig. 8A illustrates a surface 52 of an optical waveguide. On this are deposited stripes 54 of dielectric or conductive material having different physical properties from those of the material of the waveguide surface 52. The stripes are typical of the individual reflectors of an array. They may be made, for example, by vacuum deposition. Fig. 8B illustrates a second arrangement. Here the waveguide surface 52 has formed in it grooves 56 which by virtue of presenting a discontinuity of optical properties act as reflectors in an array. Such grooves may be formed, for example, by a process of ion milling. In Fig. 8C the waveguide surface 52 has diffused into it regions 58 of material having refractive index and/or density, different from the surroundings, and hence presenting discontinuities which enable the regions to act as interfaces, ie optical reflectors in an array. Examples are ion diffusion of titanium into lithium niobate; and donor or acceptor impurities into a semiconductor such as gallium arsenide. In a further arrangement, not illustrated, metal stripes deposited on the waveguide act as reflectors. Such metal reflectors may be made, for example, by conventional photolithographic methods. The foregoing is illustrative only of the ways in which reflectors for an array may be formed, and other ways are possible. Further, the reflectors need not be in the form of stripes; each reflector can be an arrangement of dots of material differing in properties from the surroundings. The reflectance of such a reflector can be controlled not only by the material of which the dots are formed, but also by the shape, size and spacing of dots within the area occupied by the reflector. The weighting of array reflectors has been mentioned above, with reference made to Fig. 5. Further examples are illustrated in Figs 9A and B. Fig. 9A illustrates weighting through variation of groove size 64; while Fig. 9B instances variation in dot density 66, from reflector to reflector 68. Variable spacing of reflectors in a chirped array may be arranged, for example, by preparing a large scale picture of the array, and then reducing it photographically for use in making a mask, as is done in the manufacture of electronic integrated circuits. In another method an array may be produced at final size by use of a table, the motion of which is programmed according to the required pattern of chirp, and controlled to the necessary degree of precision by interference methods using a laser beam.

The invention has been described above with reference to its use with optical-wavelength radiation. However, the invention is not restricted to optical wavelengths, and other parts of the electro-magnetic spectrum may be used. Indeed, the use of other kinds of radiation may be contemplated; for example, surface acoustic waves, or magnetostatic surface waves.

CLAIMS

1. A multiplexing and demultiplexing system for the combining and separating of information streams in which each information stream is carried by one of a plurality of not less than two beams of radiation of predetermined wave length; combining and separating of said streams being produced by combining and separating the beams carrying said respective information streams at least in part by an array of at least partially reflecting interfaces between media, so shaped and mutually arranged, in relation to the beams to be multiplexed or demultiplexed, as to combine the plurality of beams, emitted from a plurality of discrete foci, to be multiplexed into a combined beam complex; and to separate the component beams from a combined beam complex to be demultiplexed and direct said beams each to be received at one of a plurality of discrete foci.

2. A system according to claim 1 in which the combining and separating of the component beams is produced in part by an array and in part by a refractive element.

3. A system according to claim 2 in which the refractive element is a lens.

4. A system according to claim 1 in which the array has a variable spatial periodicity between the interfaces or reflectors thereof.

5. A system according to claim 4 in which

the reciprocal of the spacing between successive interfaces varies substantially linearly along the array.

6. A system according to any one of the preceding claims in which the said interfaces are curved.

7. A system according to any one of the preceding claims in which the said interfaces vary in individual size along the array.

8. A system according to any one of the preceding claims in which the interfaces are arranged as discrete stripes of a material which differs in dielectric constant and/or other physical properties from that of an adjacent continuous bulk of material.

9. A system according to any one of claims 1 to 7 in which the interfaces are arranged as grooves in a surface of a continuous bulk of material.

10. A system according to any one of claims 1 to 7 in which each interface is arranges as a pattern of dots differing in dielectric constant and/or other physical properties from that of an adjacent continuous bulk of material, the reflecting characteristics of such interface being determined by the size, shape, and/or spacing of said dots.

11. A system according to any one of the preceding claims which operates with electromagnetic radiation in the optical or near-optical regions of the spectrum.

12. A multiplexing and demultiplexing system substantially as hereinbefore described with reference to any one of the accompanying drawings.

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